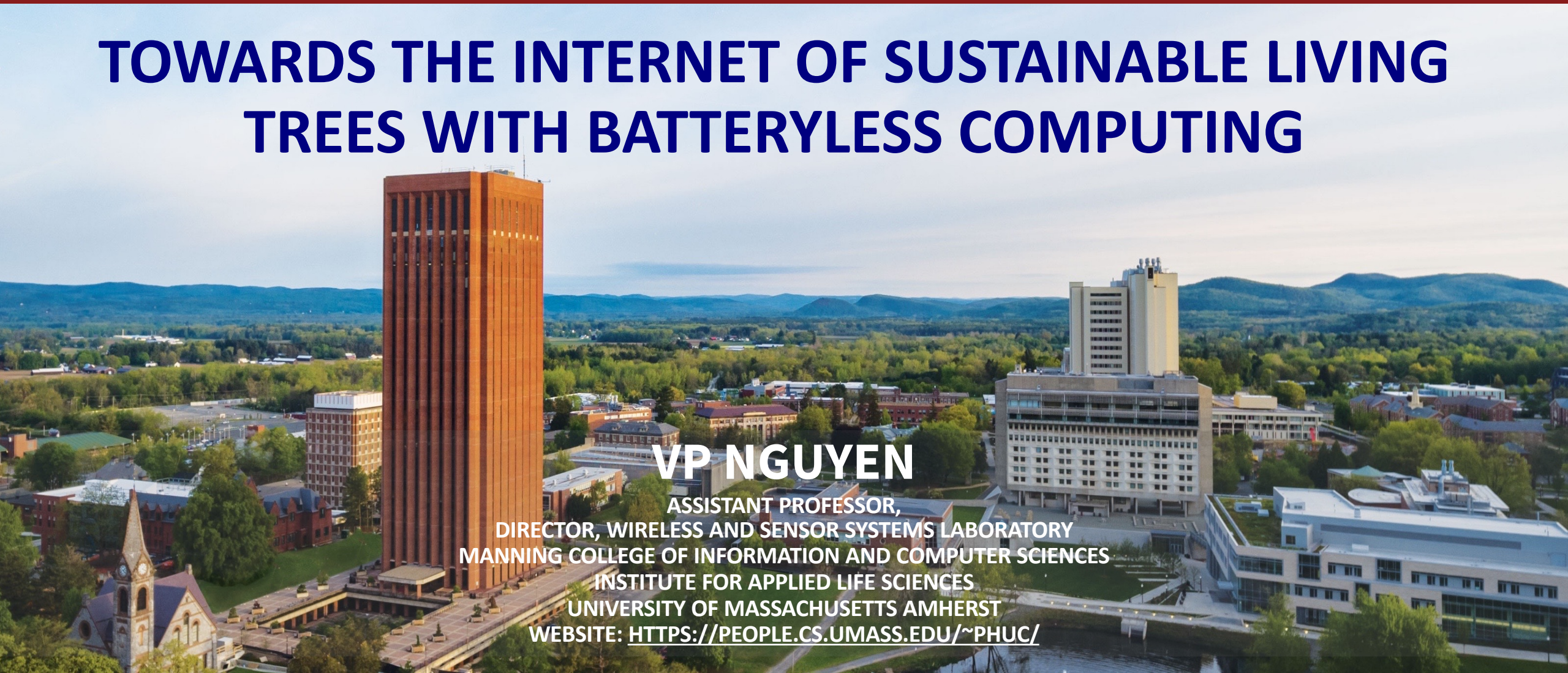
TOWARDS THE INTERNET OF SUSTAINABLE LIVING TREES WITH BATTERYLESS COMPUTING



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Wireless & Sensor Systems Lab (WSSL)

We build **computational "things"** that are **reliable, autonomous, sustainable, and scalable** for ***health & environmental monitoring.***

Fundamental computer system research contributions

Deployable designs and real-world validations

Sustainable Autonomous “Things”

Real-time **decision making.**

sense | compute | infer | intervene

Provide **useful** **function at** **low cost**

e.g., practical accuracy

Low/zero **maintenance/interference.**

Reliable & Autonomous

Sustainable & Scalable

Wireless & Sensor Systems Lab (WSSL)

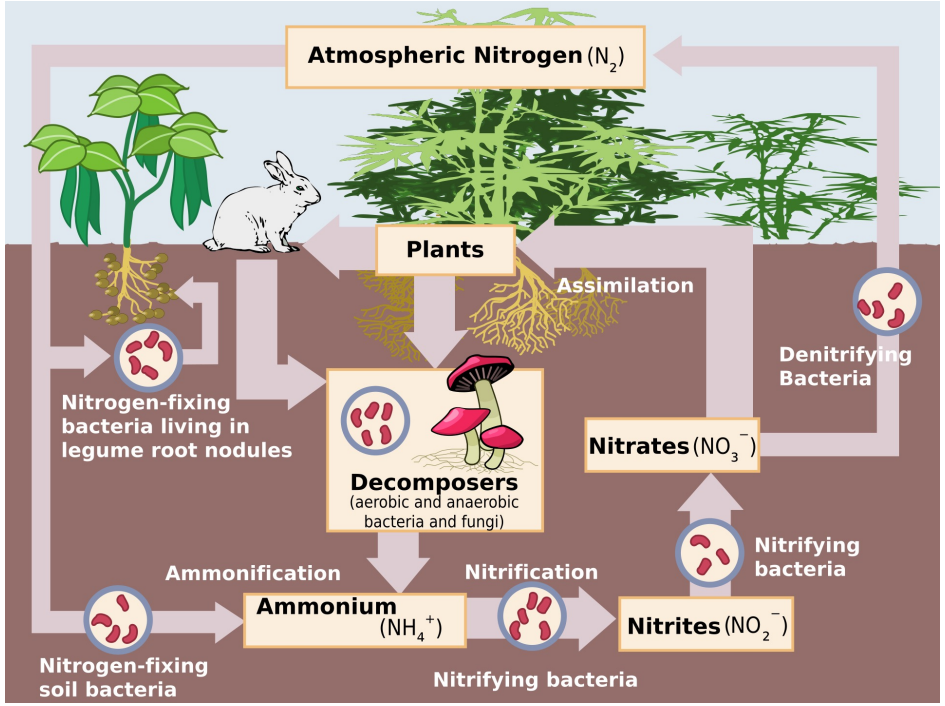
Need to produce more food in the next 50 years than in the previous ten thousand years to feed the growing population

maize, rice, & wheat
provide nearly half of the world's plant-derived calories

Growing a few varieties of plants makes our food supply vulnerable to **pests, diseases, & climate change**

Overuse of fertilizers & chemicals
less productive farmlands, less nutritious and unhealthy food

Energy Consumed by Agriculture



1% of annual world *energy* to fix nitrogen

Nitrogen use efficiency is less than 50%

Water Consumed by Agriculture

Traditional irrigation systems have an efficiency of 40%

Precision Agriculture

Artificial Intelligence
on the Cloud

Water, Fertilizer,
Pests Control

John Deere

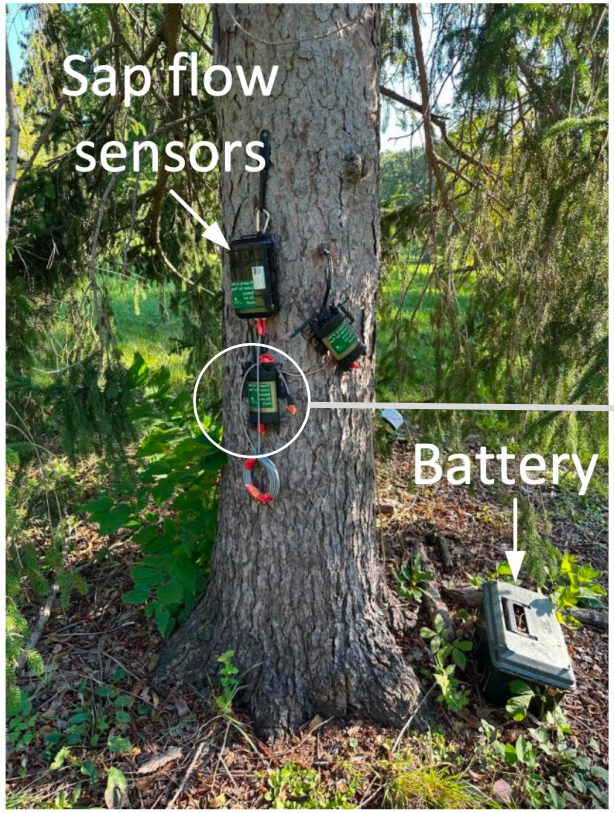
Moisture sensor ($572)
Solar Energy ($187)

- Water sensor,
- Nutrient sensor,
- Environmental sensor

Existing sensing technologies
are labor extensive and costly and do not capture signals directly from the Tree body

Sap flow Sensors

a) Sap flow sensor for small stems at USDA's farm



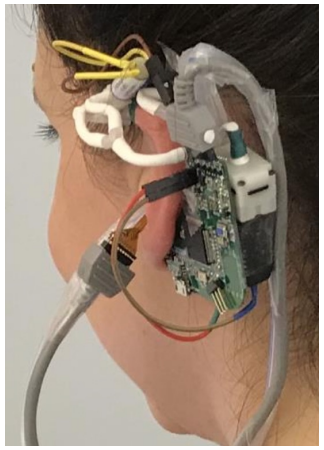
b) Sap flow sensor for large stems at Morton Arboretum

We have built many wearables for human.

Can we build wearbles to **monitor the tree health?**

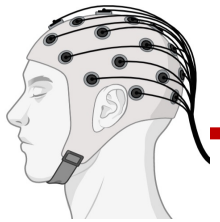
Brain Computers

Head-based Sensing

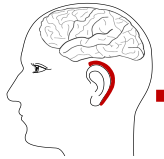


Ear-based Computers

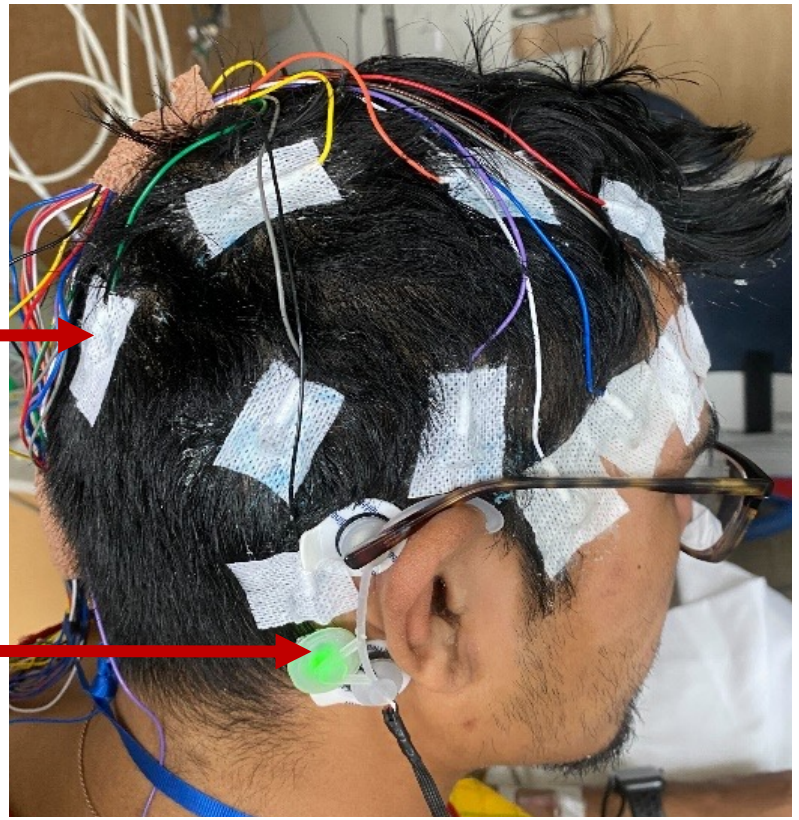
Oral Sensing



v-EEG
(Groundtruth)

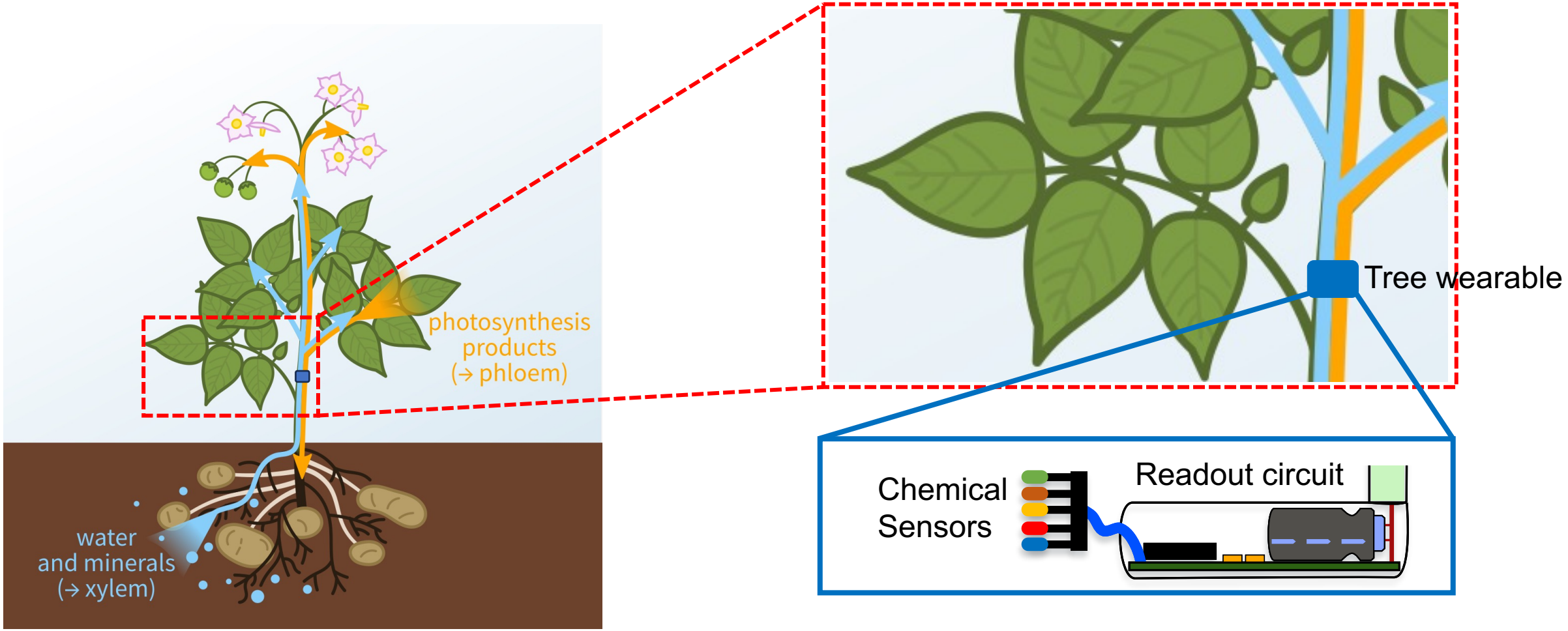


Our Wearable Device



Epileptic Seizure Monitoring System

Can we build wearables to **monitor the tree health?**

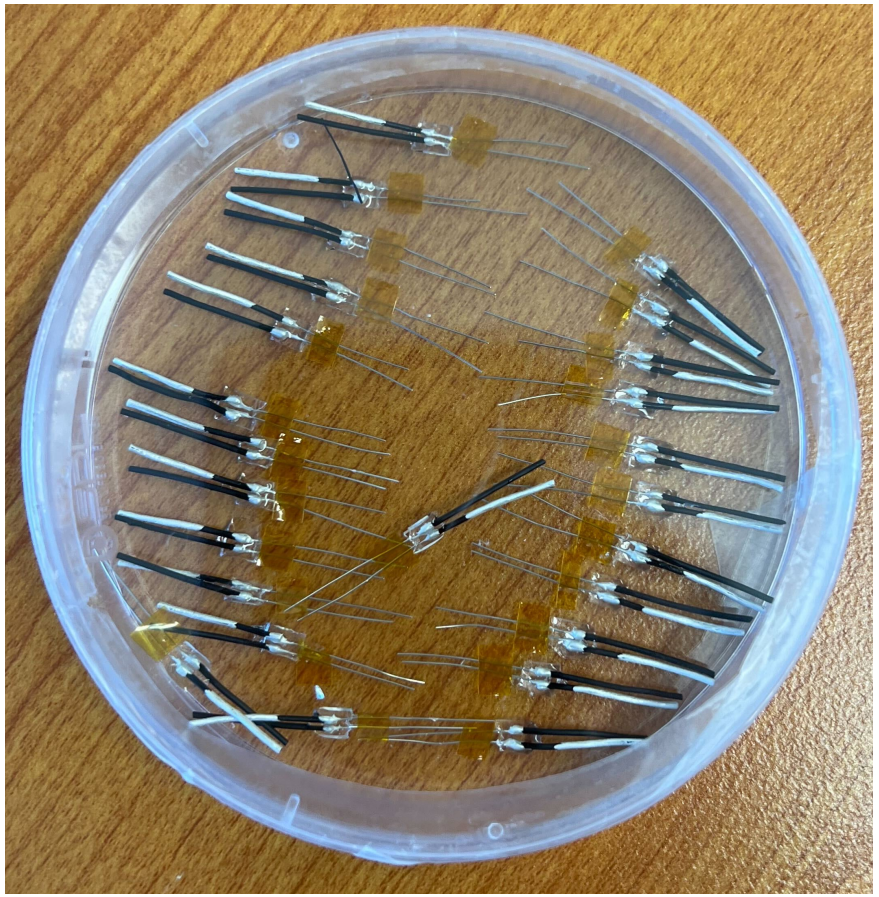


Challenges

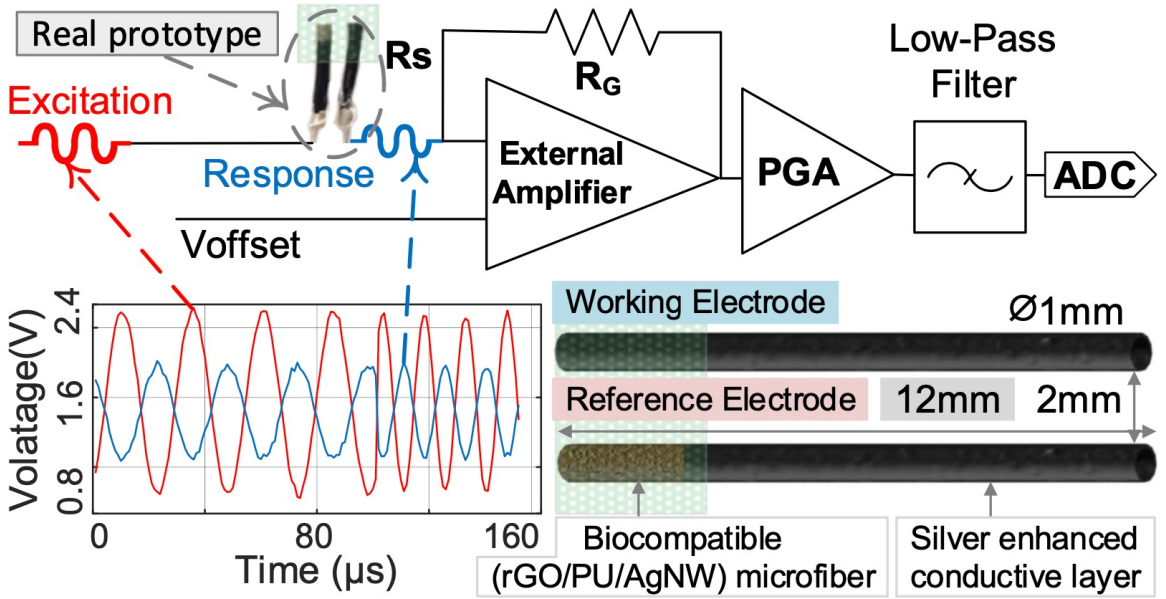
- Device can't generate negative pressure to tree [1,2,3]
- User can't collect data very often
- User can't change battery
- Device can't be costly

[1] M. Berggren and A. Richter-Dahlfors, "Organic Bioelectronics," Adv. Mater., vol. 19, no. 20, pp. 3201–3213, Sep. 2007.
[2] J. Rivnay, R. M. Owens, and G. G. Malliaras, "The Rise of Organic Bioelectronics," Chem. Mater., vol. 26, no. 1, pp. 679–685, Jan. 2014.
[3] J. T. Friedlein, R. R. McLeod, and J. Rivnay, "Device physics of organic electrochemical transistors," Org. Electron., vol. 63, pp. 398–414, Dec. 2018.

BioCompatible & Implantable Sensor

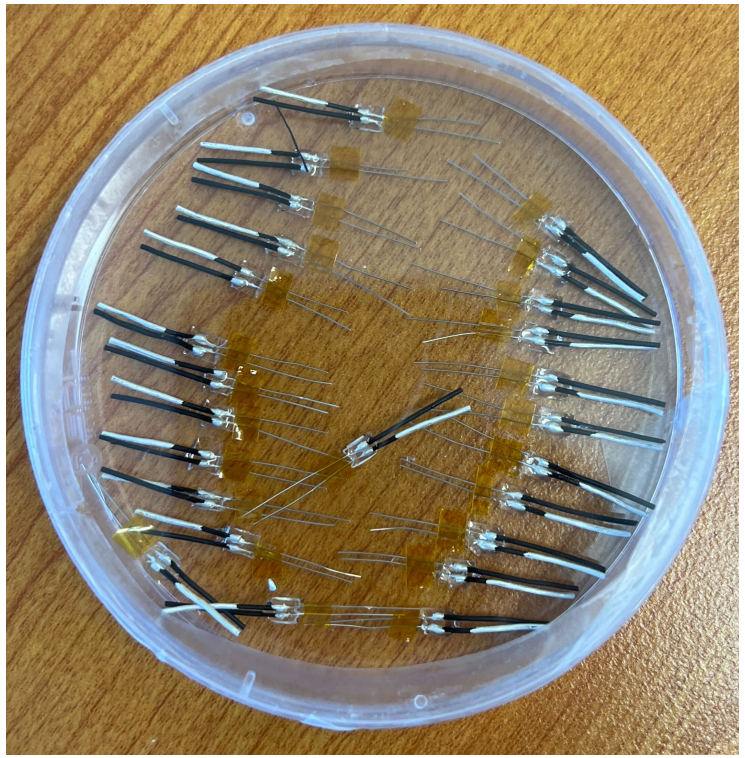


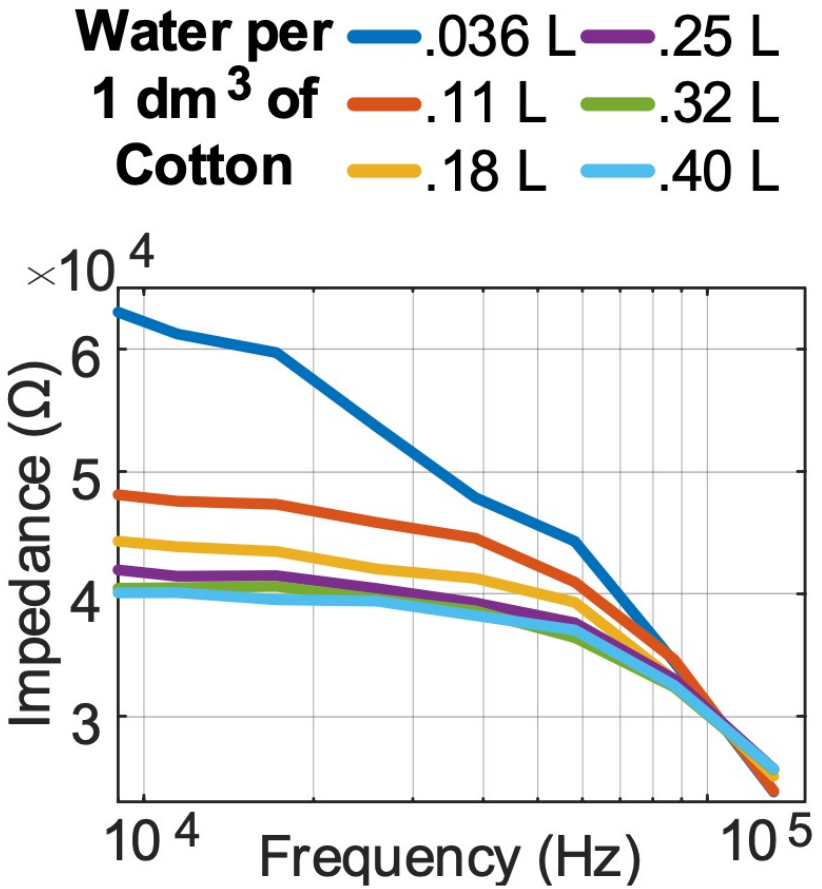
Our fabricated nutrient sensors



Readout circuit

BioCompatible & Implantable Sensor

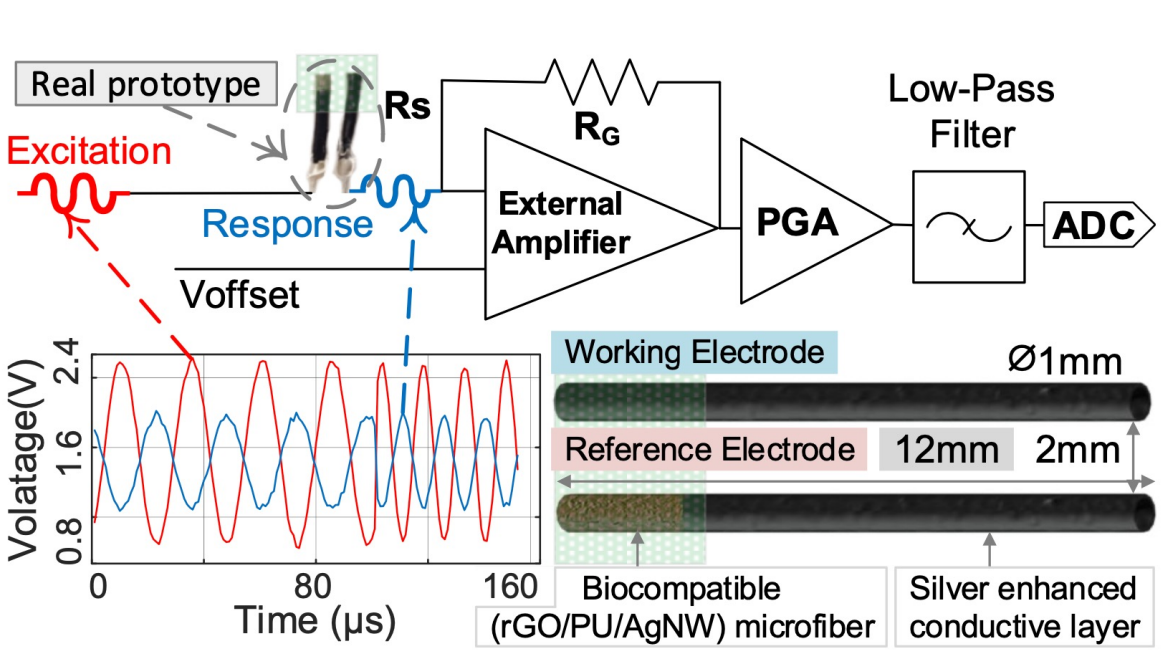


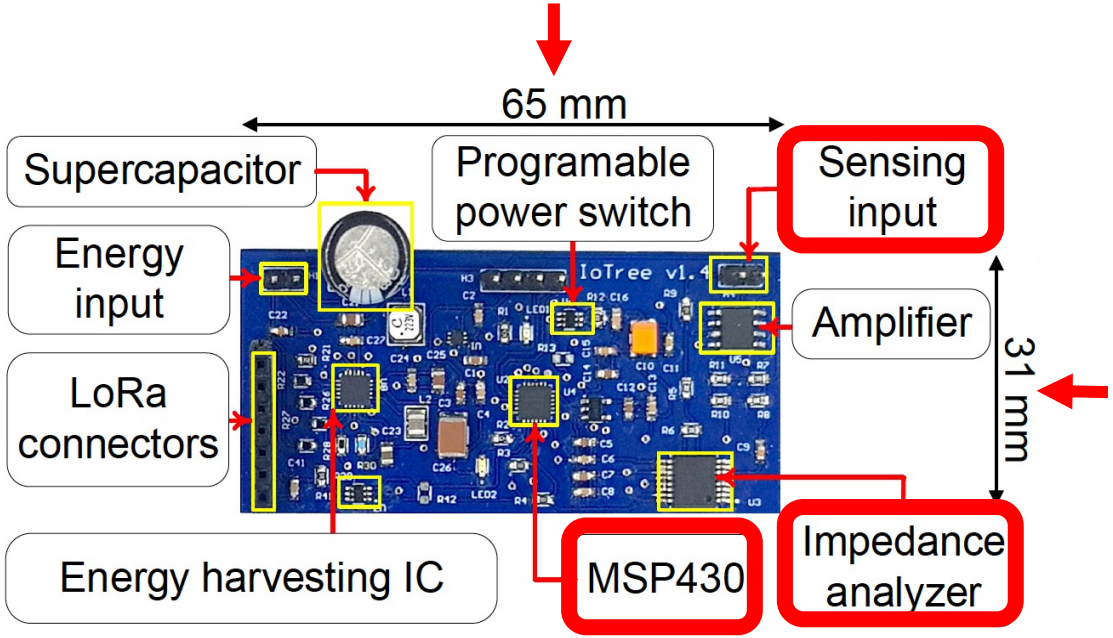


VSP Potentiostat

$4k – Costly and Bulky

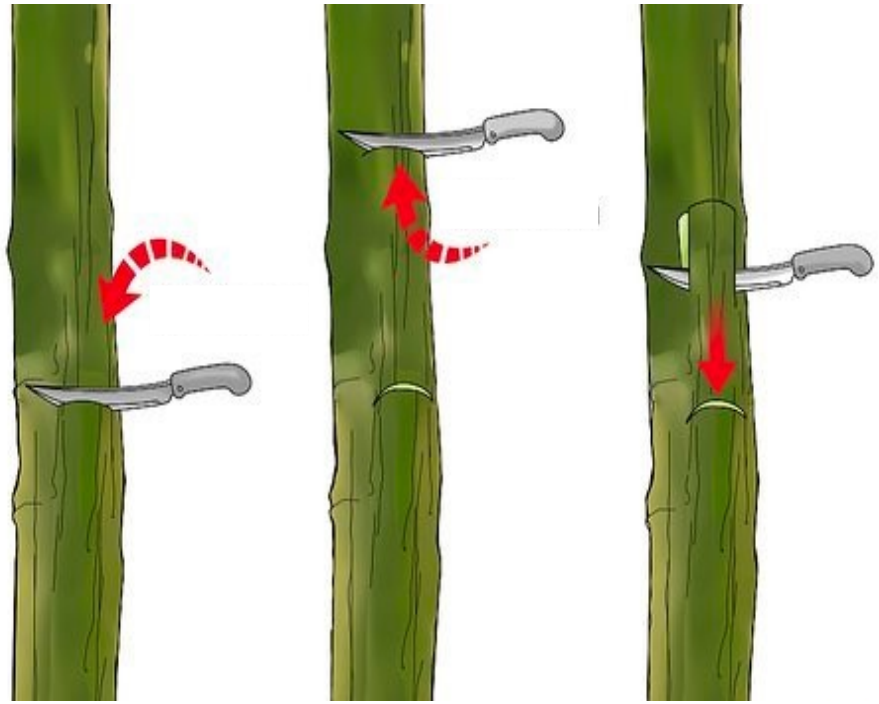
BioCompatible & Implantable Sensor





BioCompatible & Implantable Sensor

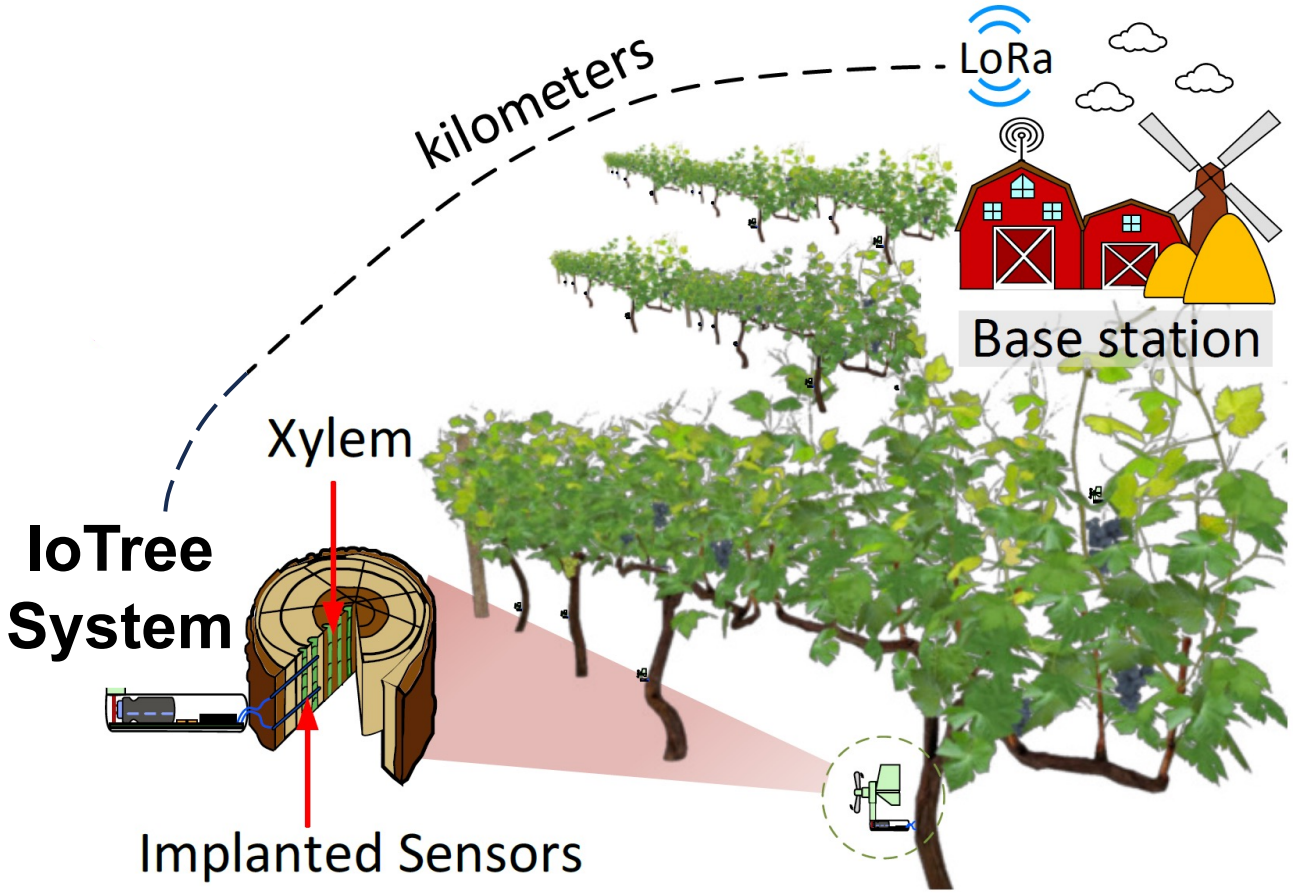
Grafting sensor into the tree body



Challenges

- ~~Device can't generate negative pressure to tree~~
- User can't collect data very often
- User can't change battery
- Device can't be costly

IoTree Communication



IoTree Communication

Wi-Fi

Energy: mW
Distance: ~50m

Programmable RFID - WISP5

Energy: uW
Distance: <10m

Cellular IoT

NB-IoT™

LTE-M

Energy: uW - mW
Distance: km
Subscription

LoRaWAN

RN2903 LoRa® Mote Board (Part # DM164139)

Energy: mW
Distance: ~km

Challenges

- ~~Device can't generate negative pressure to tree~~
- ~~User can't collect data very often~~
- User can't change battery
- Device can't be costly

Battery-free Design: Energy Harvesting

Solar energy is not available during the night

But the tree grows overnight - just like humans

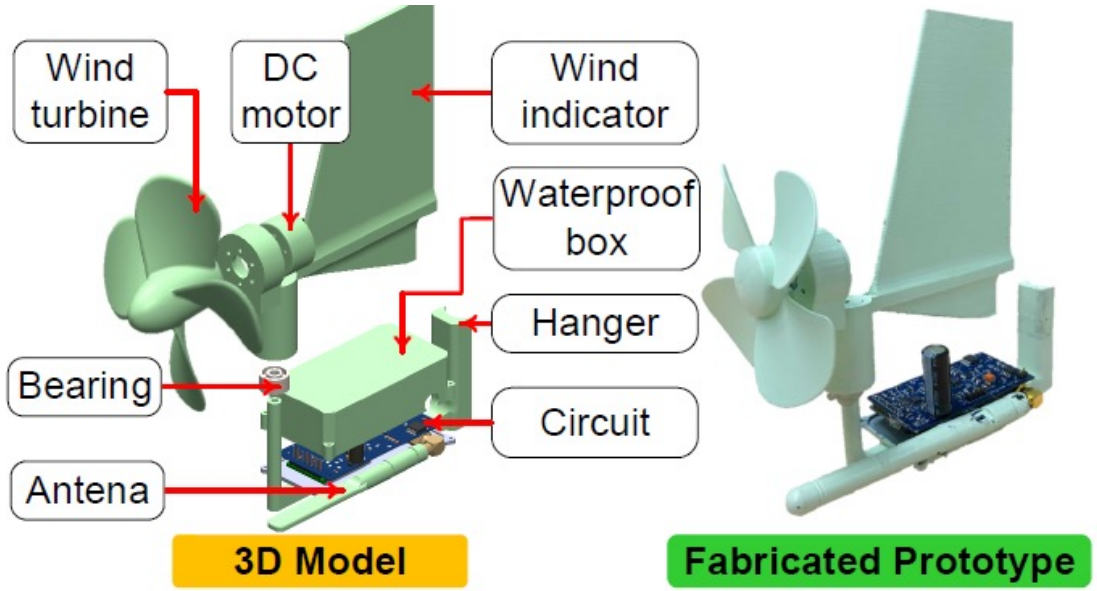
Vibration and thermal energy are not sufficient

	Idle	Sensing	Computing	Transmitting
Power (mW)	1	62	6	245
Duration (ms)	0.3	170	80	150

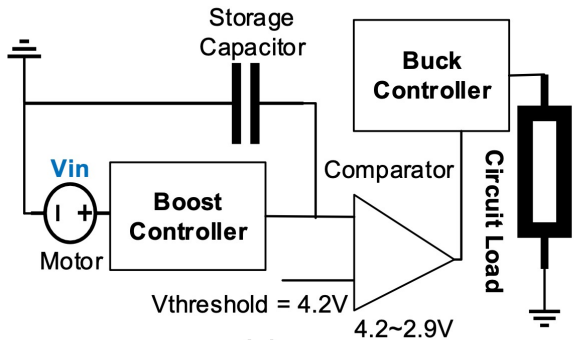
Idea:

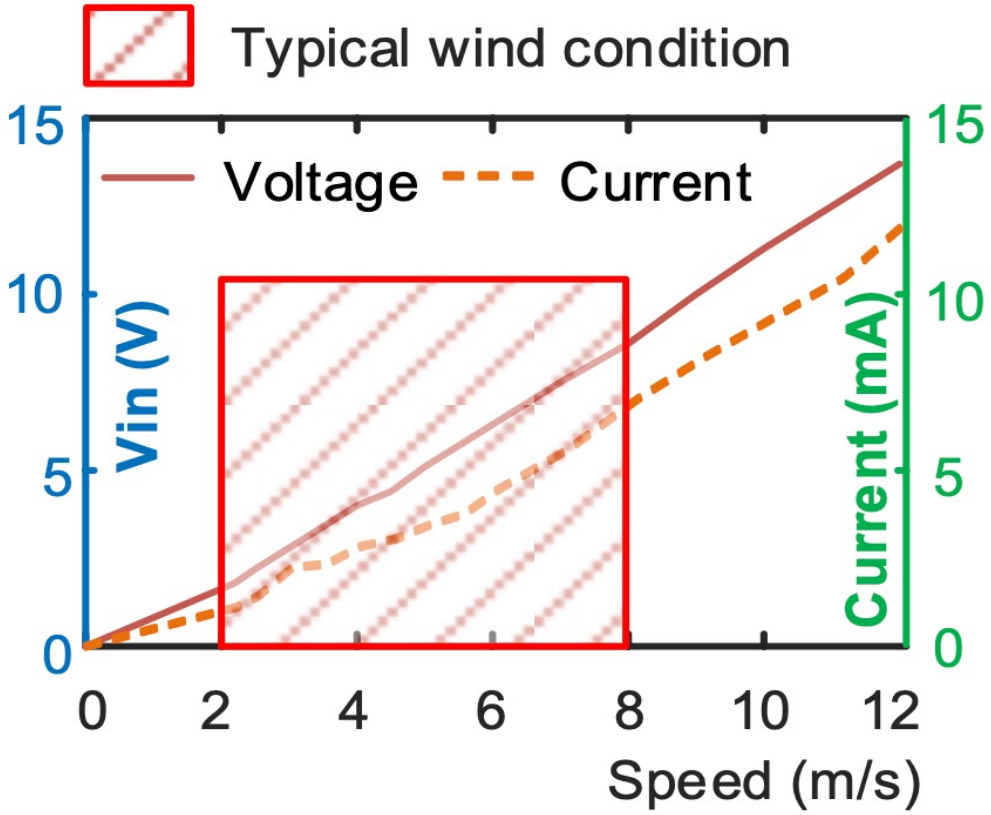
+ Wind is available almost everywhere at any time
+ Method of harvesting it is cheap

Battery-free Design: Wind Power

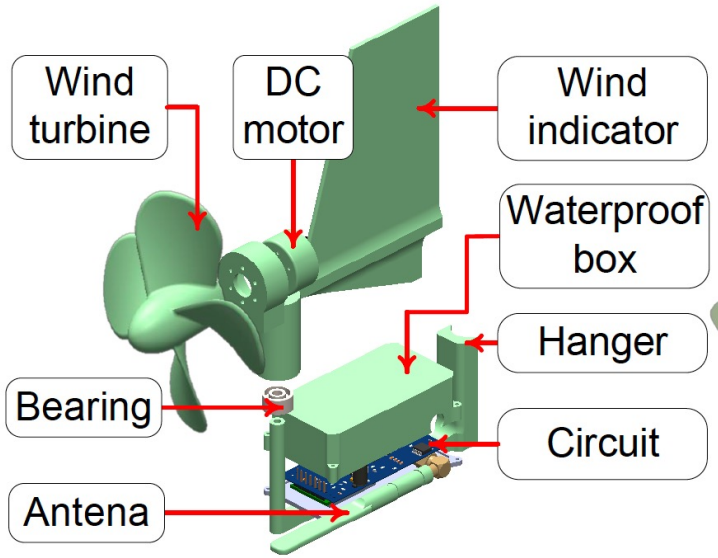


Harvesting circuit:

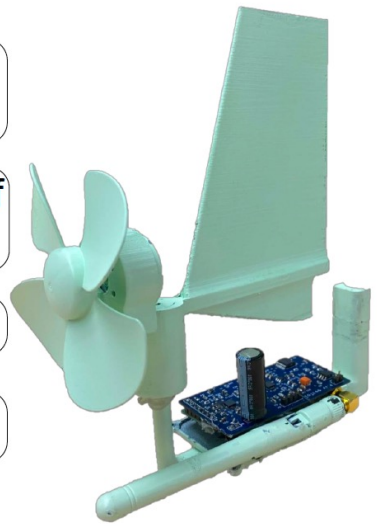




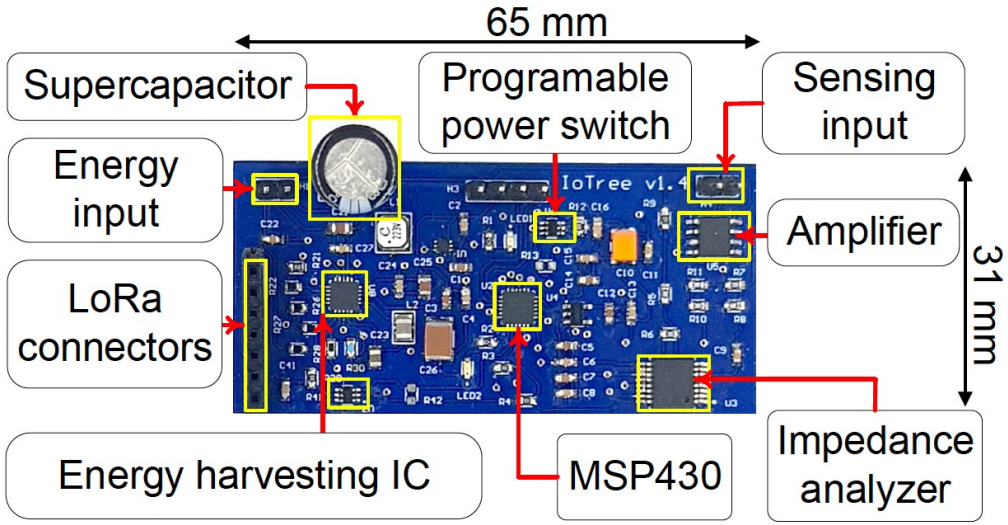
IoTree Prototype



3D Model



Fabricated Prototype

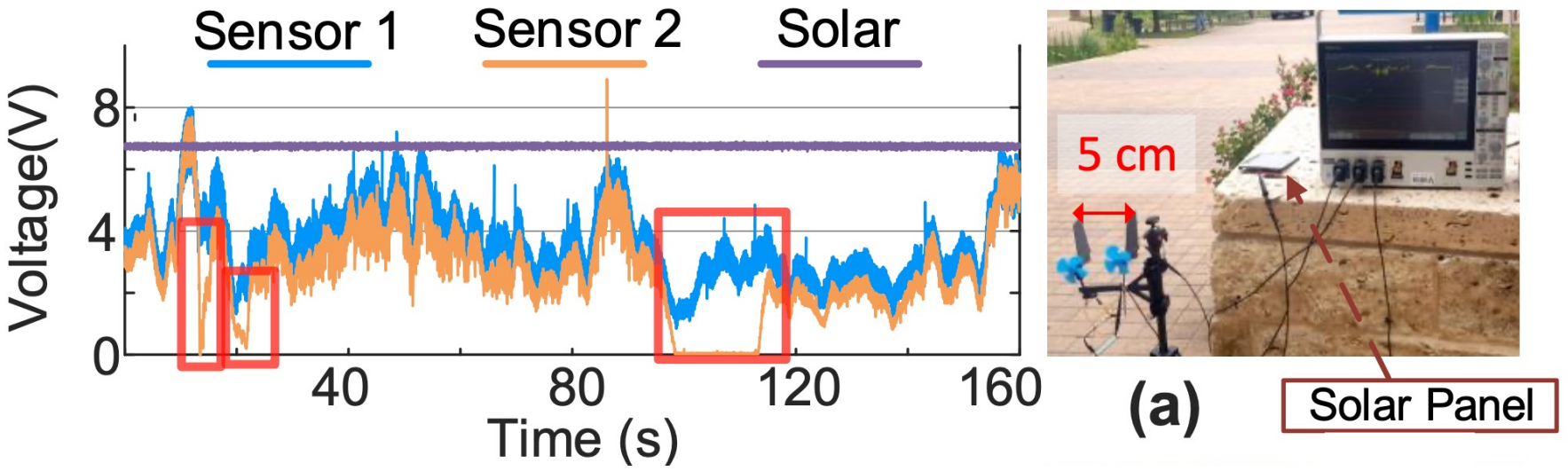


IoTree Circuit

In-the-wild Deployment

Intermittent Computing

Wind energy is unpredictable



Intermittent Computing

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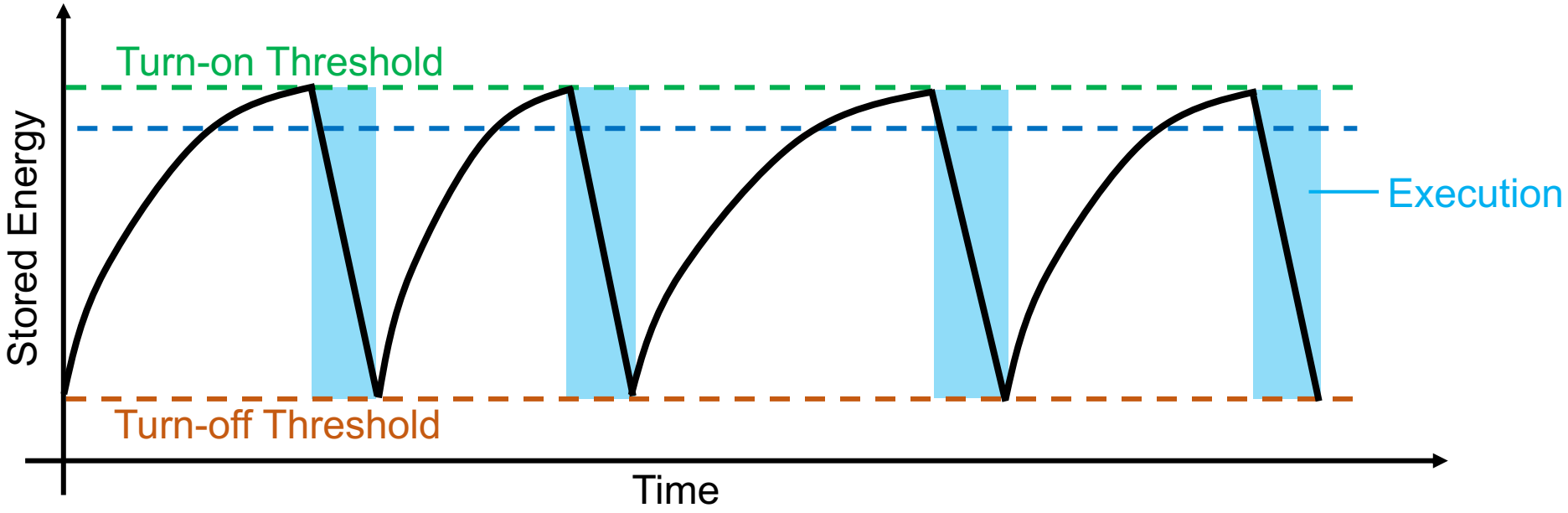
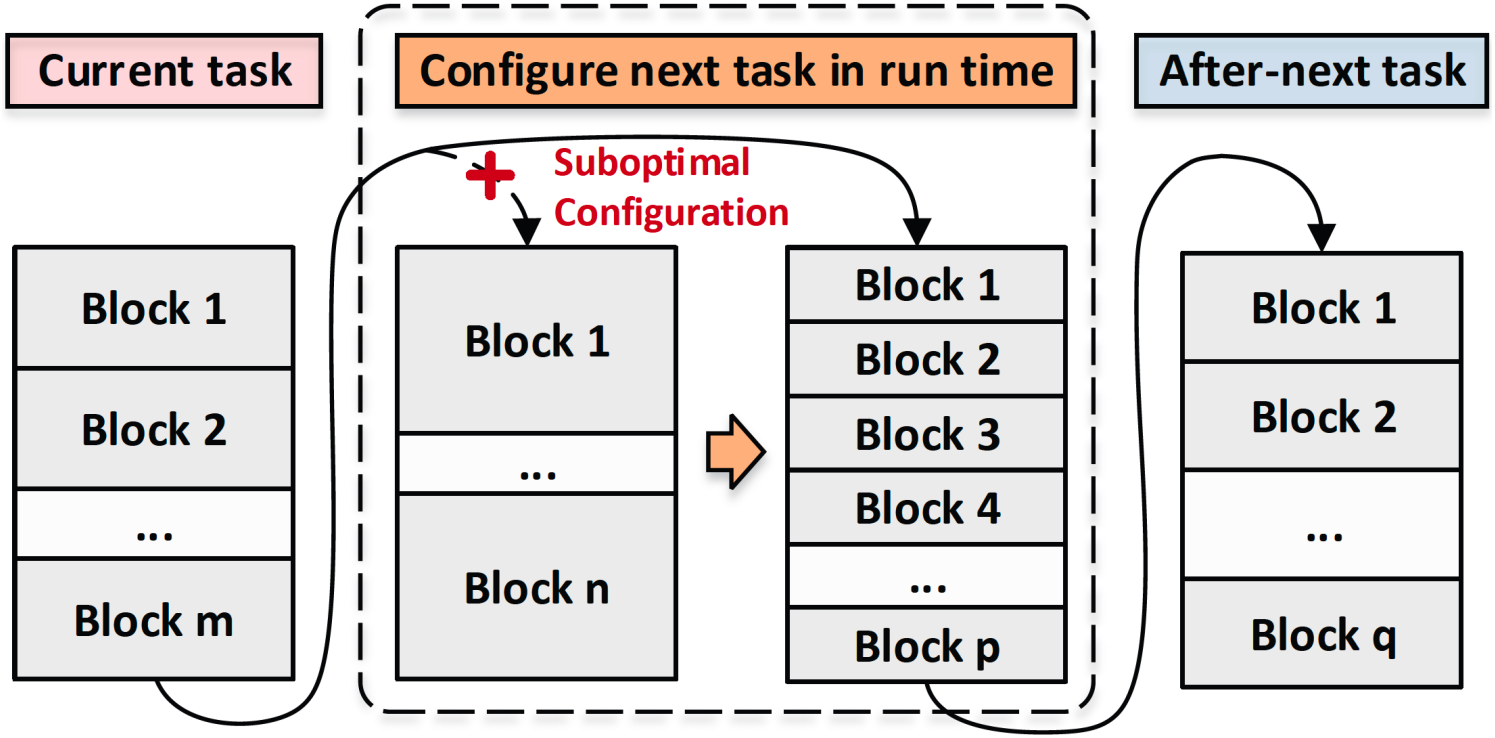


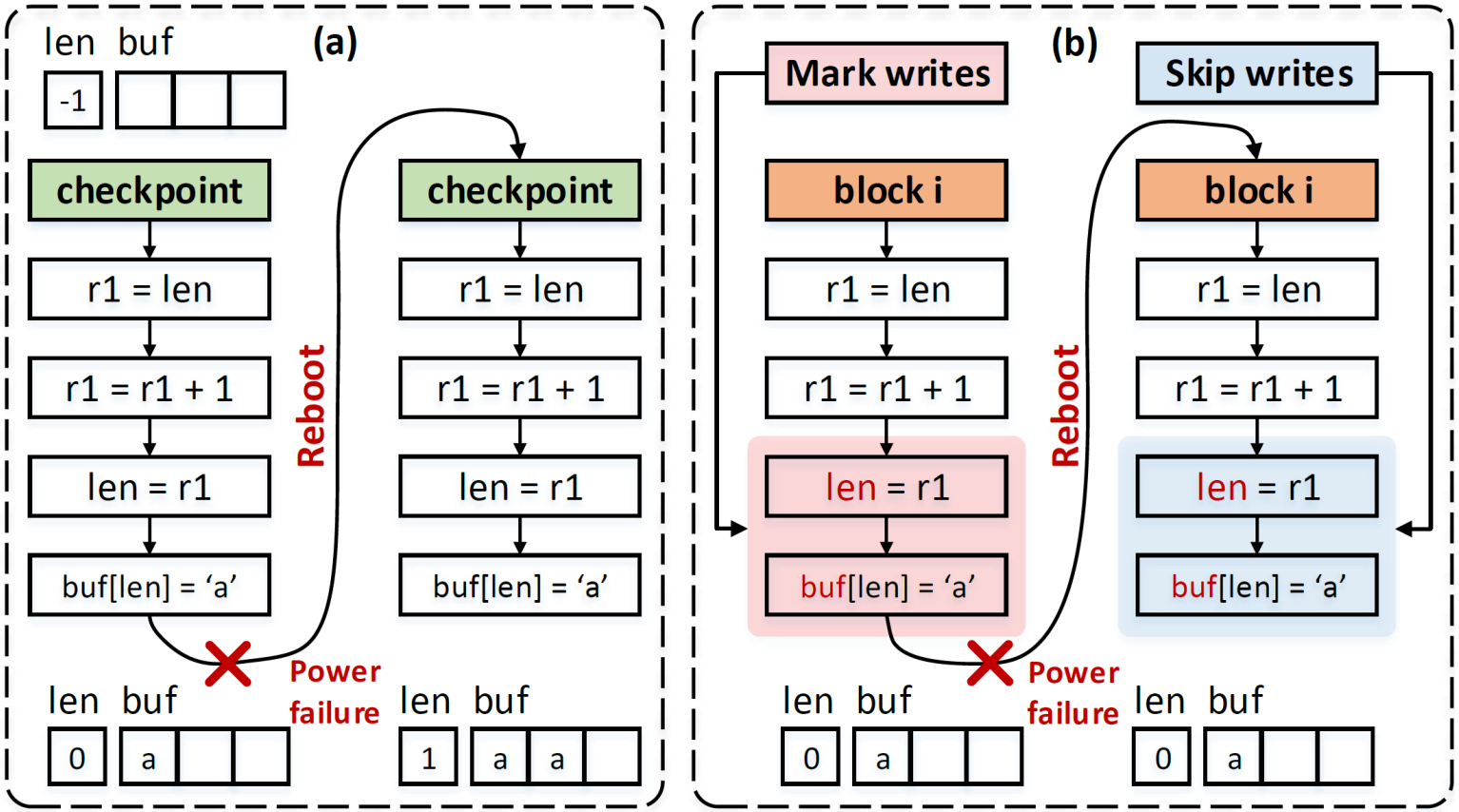
Block-based Intermittent Computing

Block-based Computing: **Size of executed code changes adaptively depending on the availability of energy during device's runtime**



Block-based Intermittent Computing

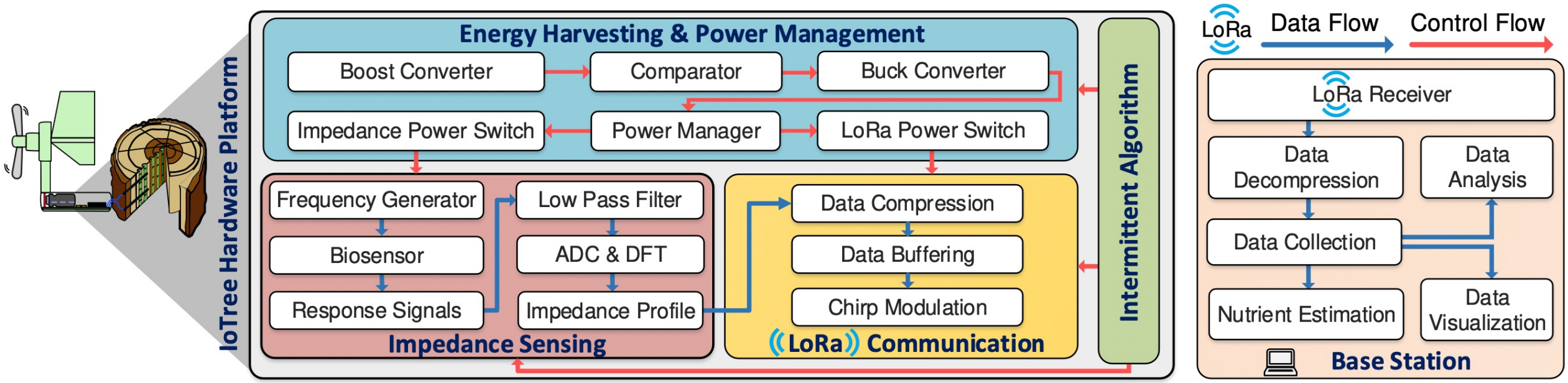
Non-volatile buffer manager avoids idempotent violation



Challenges

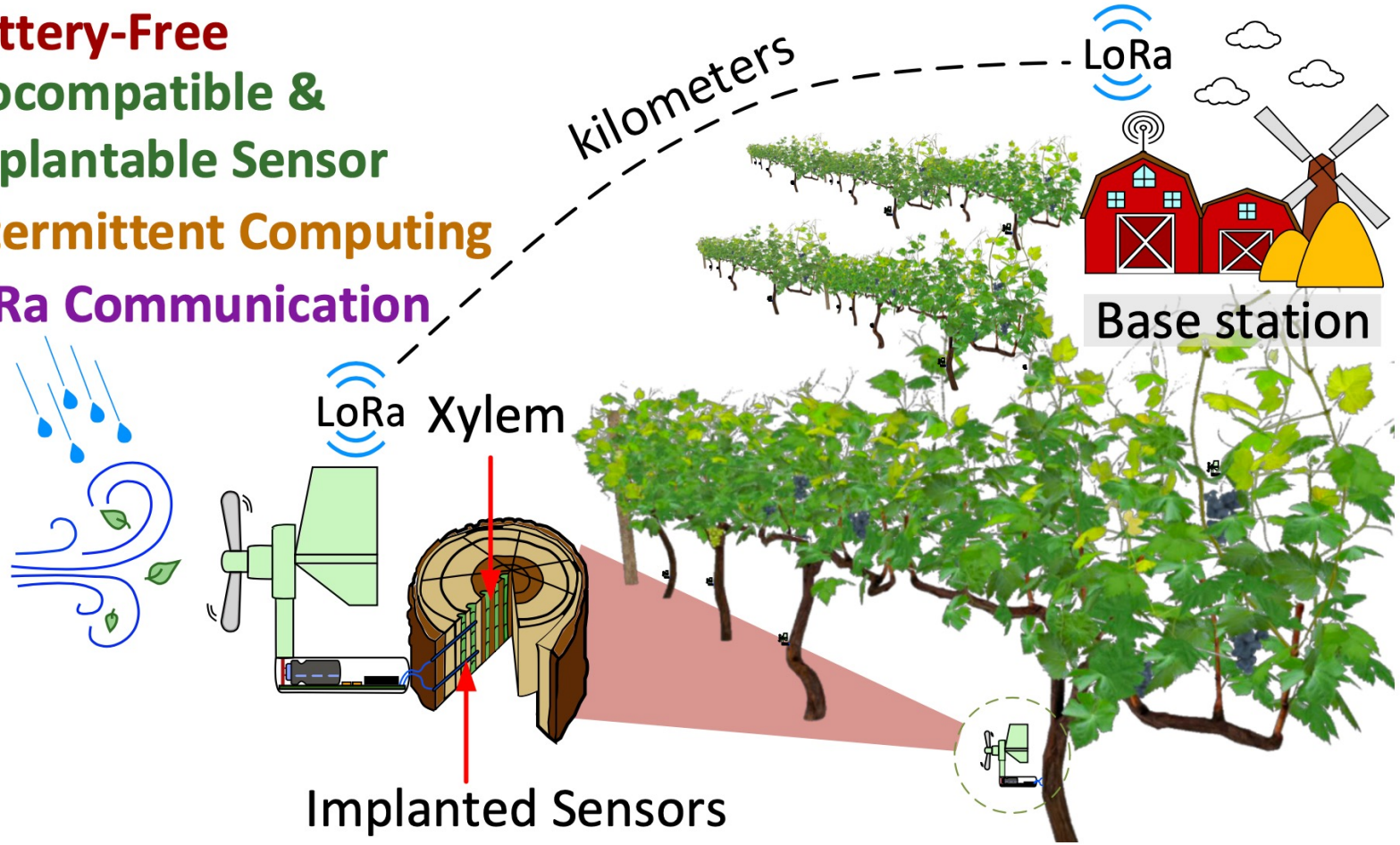
- ~~Device can't generate negative pressure to tree~~
- ~~User can't collect data very often~~
- ~~User can't change battery~~
- ~~Device can't be costly~~

IoTree System: Putting Things Together

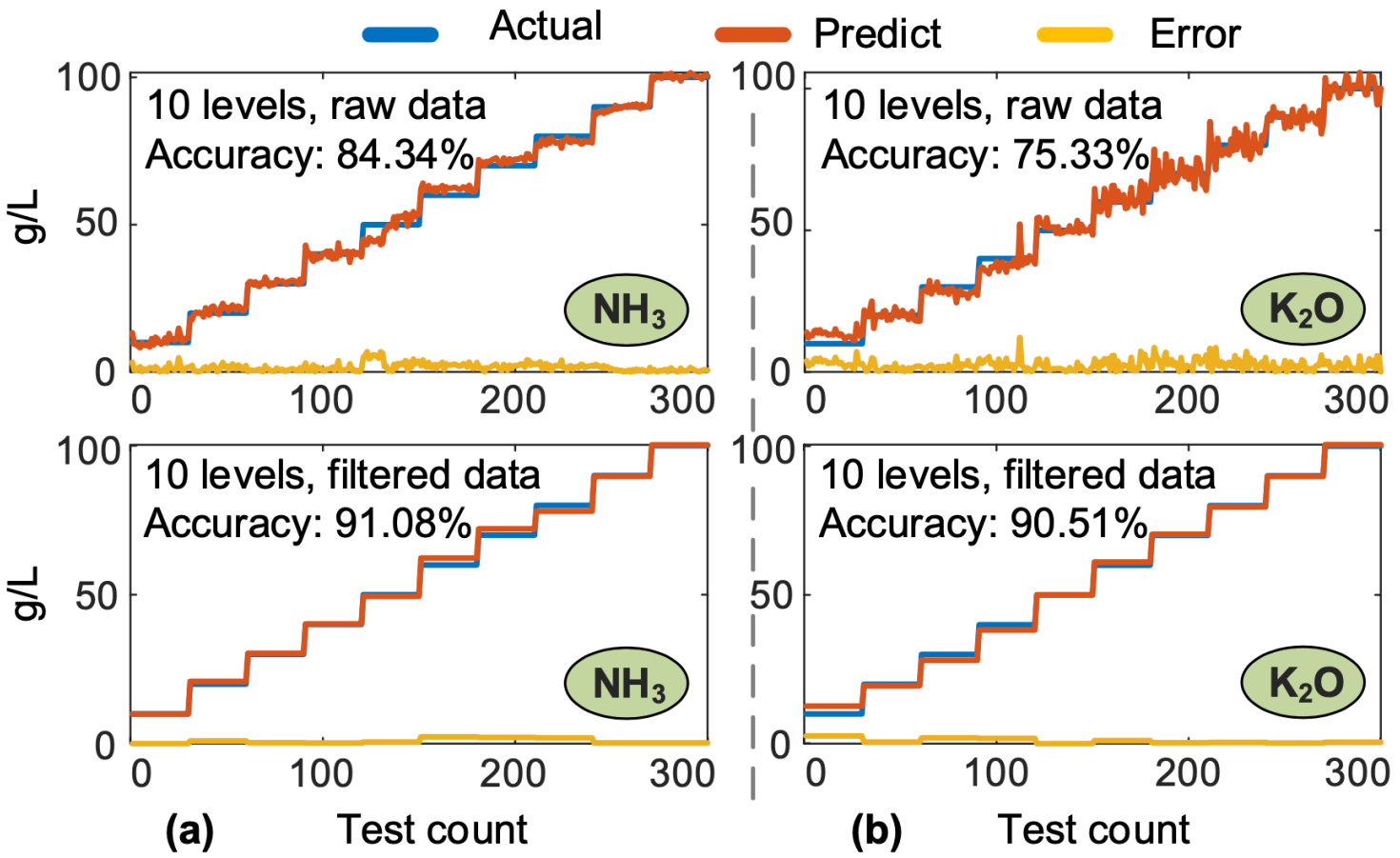


IoTree System: Putting Things Together

Battery-Free
Biocompatible &
Implantable Sensor
Intermittent Computing
LoRa Communication



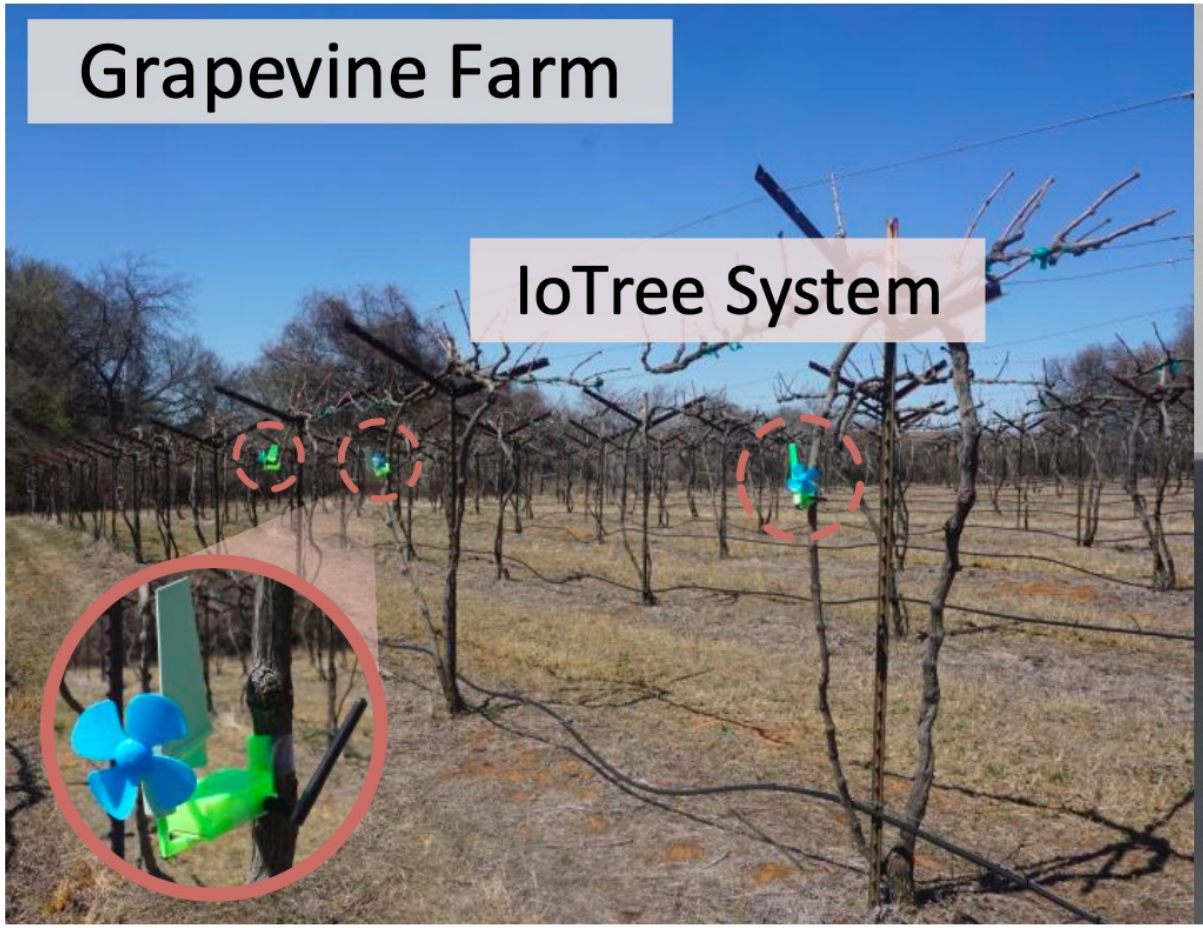
In-Lab Evaluation Results

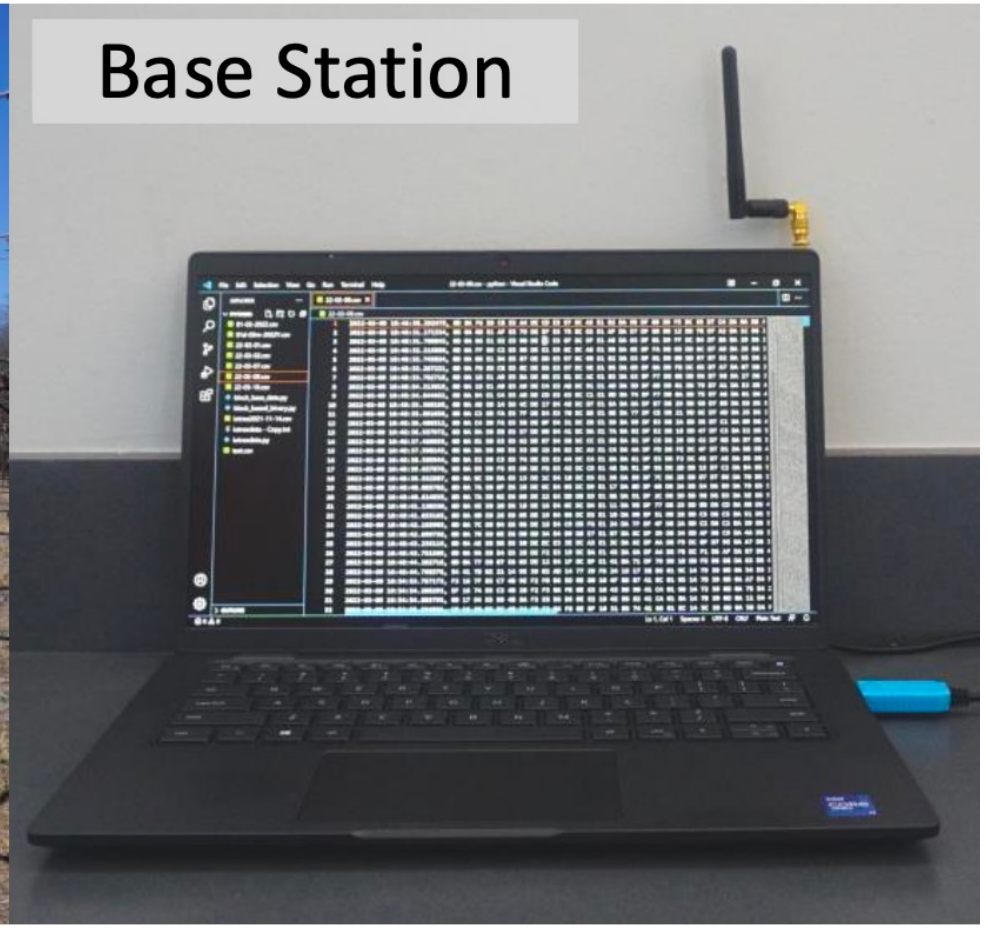


IoTree: A Wearable System for Plant's Health Monitoring (Video Demo)

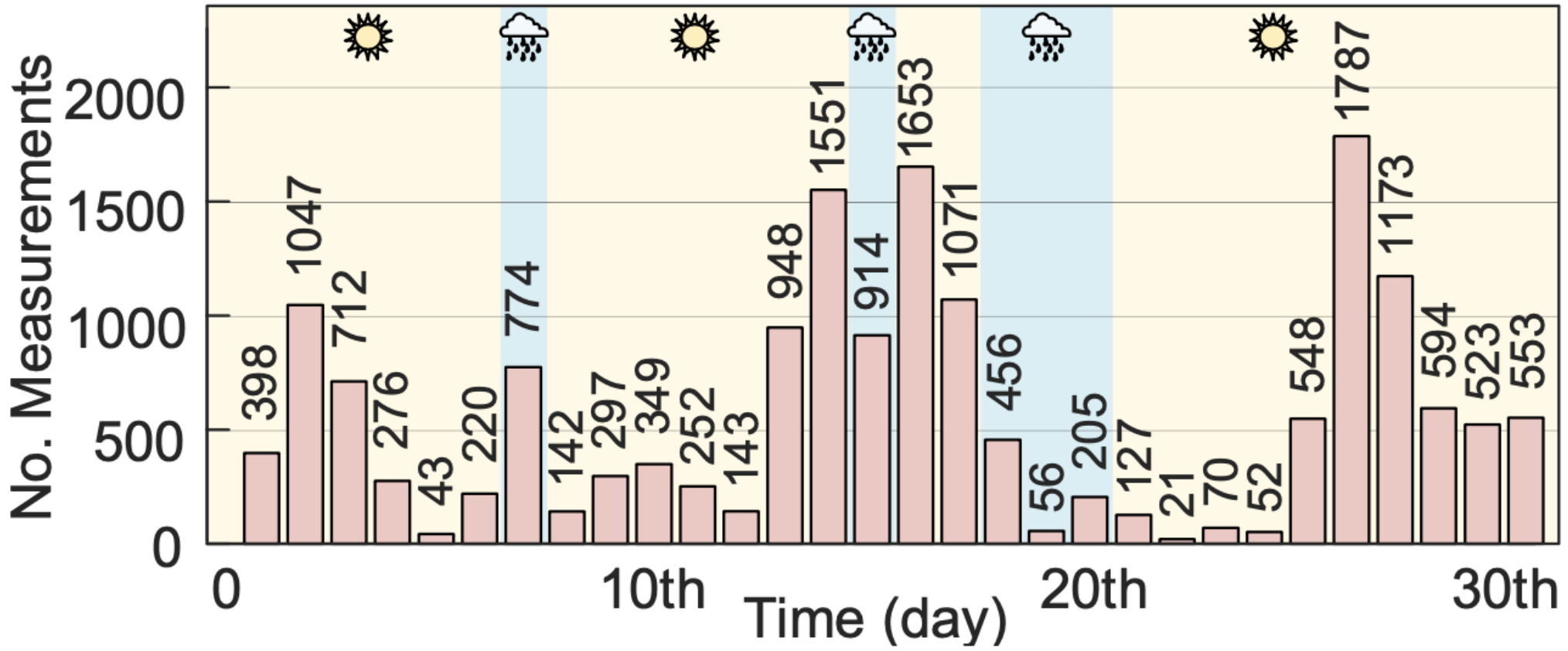
IoTree

1 Month Experiment

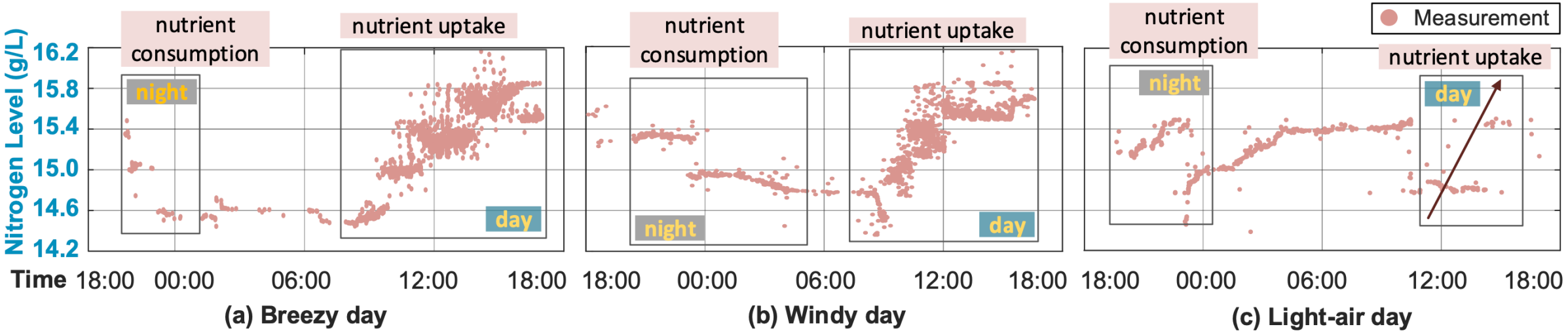




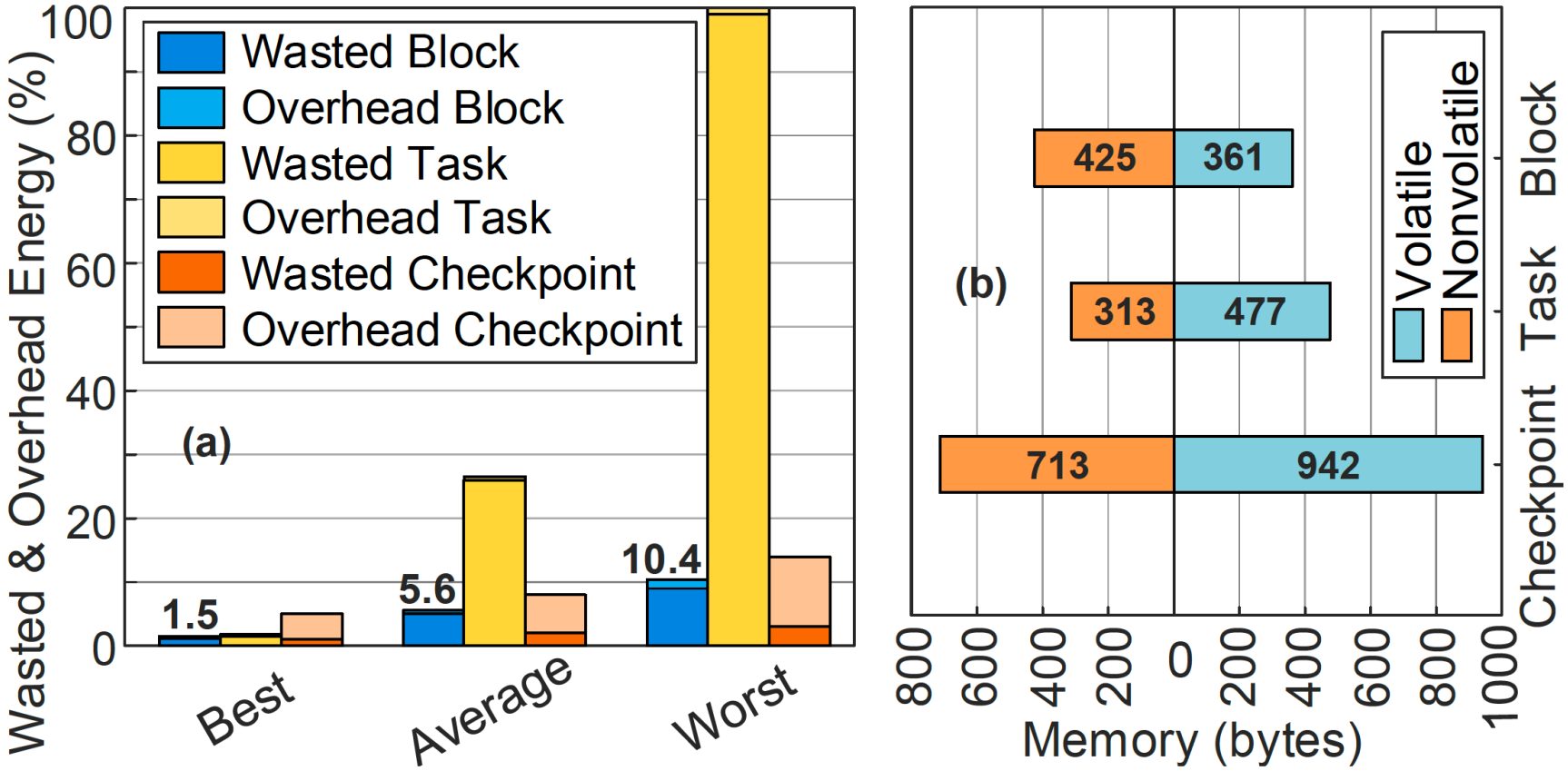
1 Month Experiment



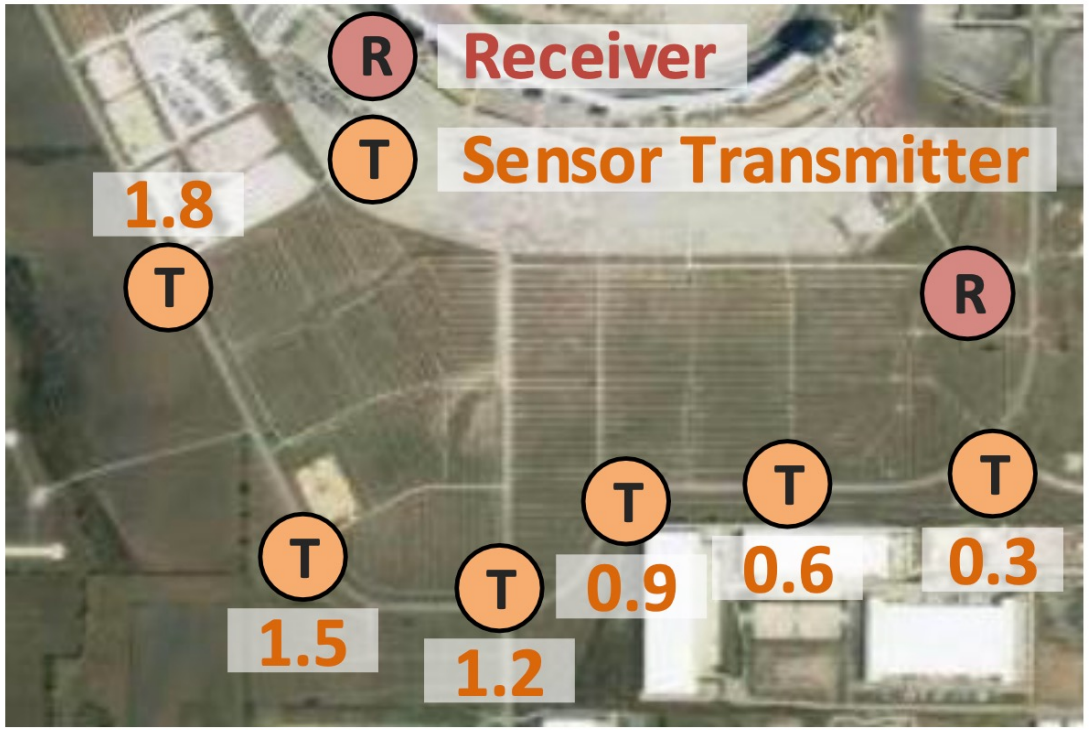
1 Month Experiment

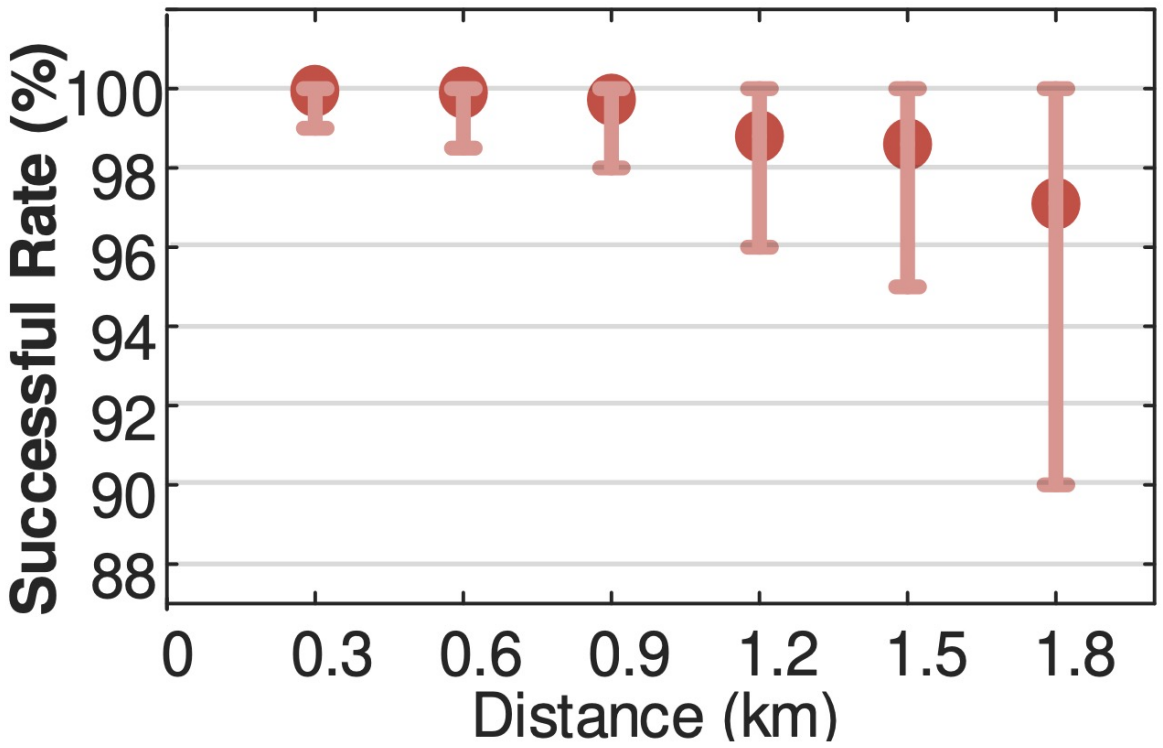


Performance of Block-based Computing



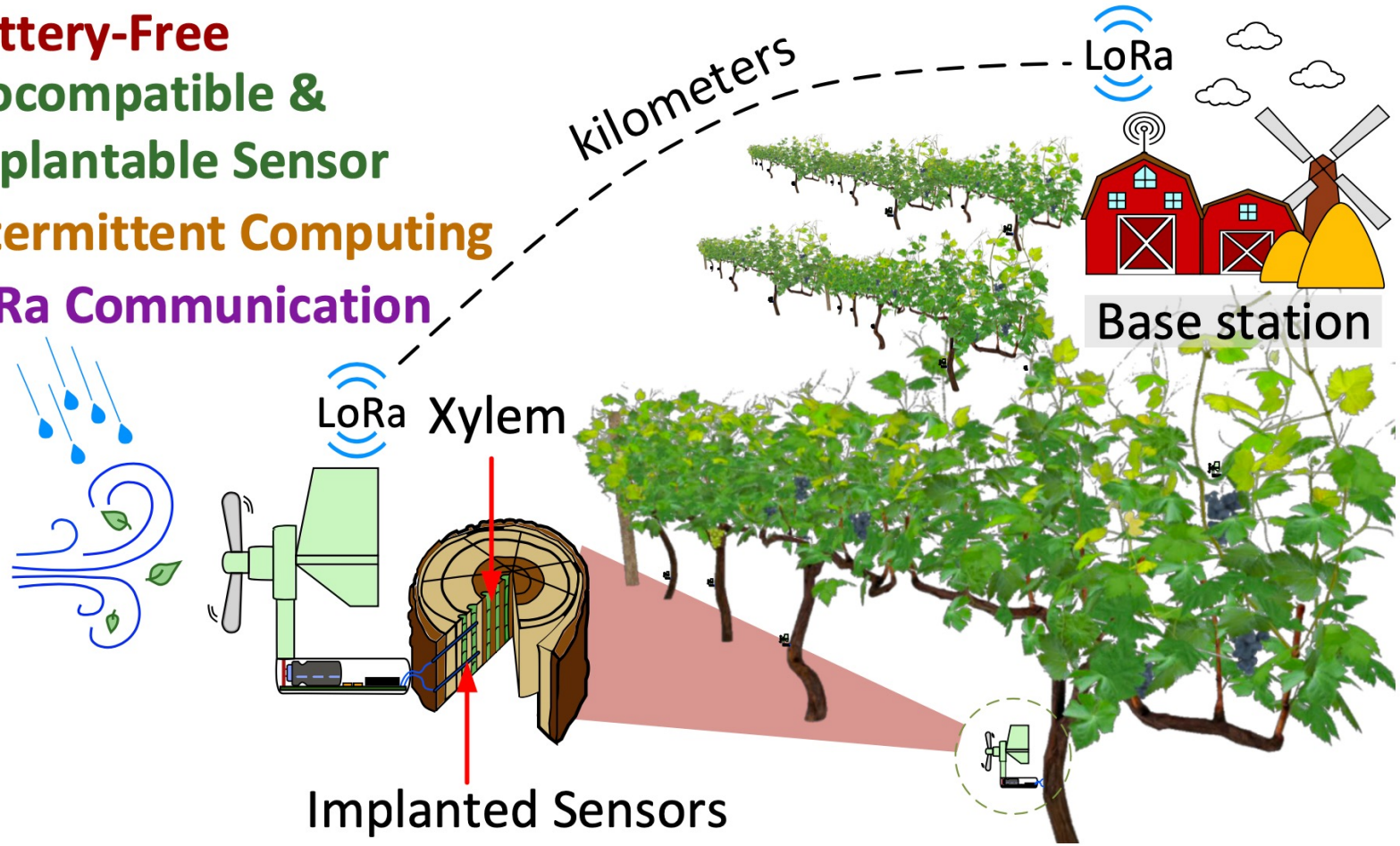
Communication Range





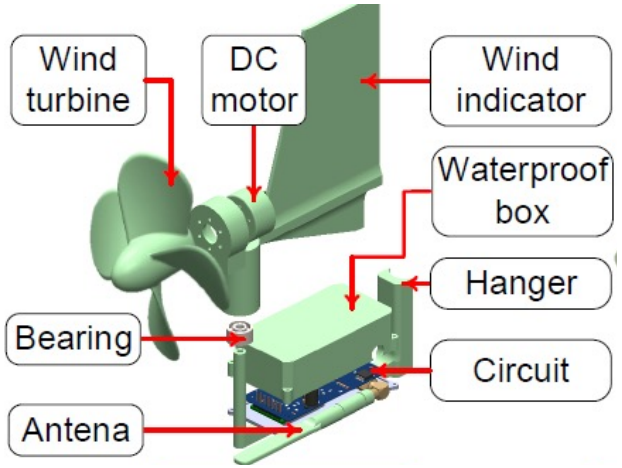
Recap: IoTree System

Battery-Free
Biocompatible &
Implantable Sensor
Intermittent Computing
LoRa Communication



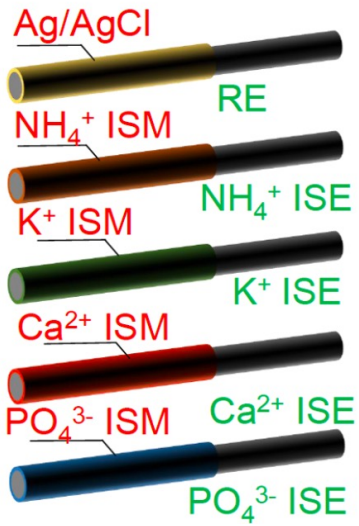
Conclusions and Future Works

We present *IoTree*, a low-maintenance, wind-powered, battery- free, biocompatible, implantable, tree wearable, and intelligent sensing system to monitor water and nutrient levels inside a living tree for precision agriculture



Future Works

Sensing more nutrients



Testing on multiple types of trees and crops

Full season evaluation

QUESTIONS & ANSWERS

University of Massachusetts Amherst